New Functions to Model Measured Deposition and Resuspension Rates of Particles

Lengweiler, P. ; Moser, A. ; Nielsen, Peter V.

Publication date:
1999

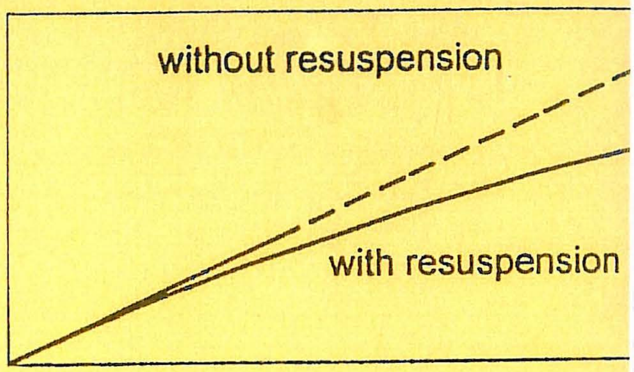
Document Version
Publisher's PDF, also known as Version of record

Aalborg **UNIVERSITY**

New Fun

New Functions to Model Measured Deposition and Resuspension Rates of Particles

P. Lengweiler, A. Moser, P. V. Nielsen



Paper No 99

Indoor Environmental Engineering

In: Proceedings of Indoor Air '99, 8th International Conference on Indoor Air Quality and Climate, Edinburgh, Scotland, 1999, Vol. 4, pp. 1049-1054

Printed at Aalborg University

New Functions to Model Measured Deposition and Resuspension Rates of Particles

P. Lengweiler, A. Moser, P. V. Nielsen

NEW FUNCTIONS TO MODEL MEASURED DEPOSITION AND RESUSPENSION RATES OF PARTICLES

P. Lengweiler[1], A. Moser[1], P.V. Nielsen[2]

[1]Air&Climate Group, Research in Building Technology, ETH Zürich, Switzerland
[2]Dep. of Building Technology and Structural Engineering, Aalborg University, Denmark

ABSTRACT

New functions to model deposition and resuspension rates based on experimental data are introduced. Deposition and resuspension are presented in dependence on the surface orientation as well as on the turbulent kinetic energy of the air. Moreover, the development of the dust building up on the surfaces is shown as a function of time.

Particles in indoor air can affect the health of people. Deposition on indoor surfaces is an important removal mechanism to reduce the airborne particle concentration. As a basis to develop methods to eliminate dust related problems in rooms, there is a need for better understanding the mechanism of dust deposition and resuspension.

With an experimental set-up the dust load on surfaces in a wind tunnel can be measured as a function of the environmental and surface characteristics and the type of particles under controlled laboratory conditions. From these results the deposition velocity and resuspension rate can be determined and, in combination with CFD, the health risk of a room and its change over time might be predicted.

INTRODUCTION

Indoor air contains particles which can affect the health of people, whether the particles themselves or contaminants transported by the particles. To study the health risk for occupants in a room it is necessary to find out which kind of particles are suspended in the air, where they come from, how they are transported and distributed in the air. A dominant process for reducing the airborne particle concentration is deposition on surfaces [1]. On the other hand, walking into a room results in resuspension which can double the amount of suspended particles. Therefore the physical processes of deposition and resuspension have to be well understood before predictions of the health risk of a room are attempted by e.g. Computational Fluid Dynamics (CFD).

A large number of experiments and CFD simulations are reported in the literature to describe type and size of particles, sources of the particles and their distribution and transportation to the boundary layer of room surfaces. But only in a few experiments deposition is considered and in even fewer resuspension. The existing CFD models contain no or only very simple models for the deposition. And many authors ignore resuspension altogether.

The aim of the presented research is to define functions which are the bases for modelling the mechanism of deposition and resuspension of particles. With these models predictions of the health risk of a room can be simulated by CFD.

METHODS

To establish a model to calculate deposition velocities and resuspension rates with CFD, a simple basic approach is investigated. The unknown parameters of this approach can be determined with experiments.

Modelling dust load

The amount of particles laying on a surface is called the dust load Φ, measured in mass per unit area. The change of the dust load over time is defined as the difference between the amount of particles depositing on the surface and the amount of particles resuspending from the surface.

$$\frac{d\Phi}{dt} = s_a - s_r \tag{1}$$

where s_a is the local rate of settling particles on the surface and s_r is the local rate of removal of particles from the surface.

Both, the rate of settling and removal of particles are dependent on the environmental conditions like air flow, surface conditions, type and size of particles as well as other forces, e.g. electrostatic charge. Deposition is assumed to be proportional to the airborne dust concentration while resuspension is proportional to the actual dust load on the surface. Hence, s_a and s_r can be rewritten as

$$s_a = ac_e \tag{2}$$

$$s_r = r\Phi \tag{3}$$

where a is the deposition velocity, r the resuspension rate and c_e the local particle concentration at the edge of the boundary layer. The units of a and r are mass per unit time and 1 per unit time, respectively.

The solution of equation (1) is fairly complicated for the general case where all parameters are dependent on time. However, for the presented case where a wind tunnel is used to carry out the experiments, constant environmental conditions over time can be assumed, i.e. the air flow and the airborne dust concentration are constant. Hence, only the dust load will change over time. Thereby the solution of equation (1) is

$$\Phi = \left(\Phi_0 - \frac{ac_e}{r}\right) e^{-rt} + \frac{ac_e}{r} \tag{4}$$

for the case where resuspension is observed, i.e. $r \neq 0$, and for the case without resuspension, i.e. $r = 0$ the solution is

$$\Phi = \Phi_0 + ac_et \tag{5}$$

where $\Phi_0 = \Phi(t = 0)$ is the dust load at the beginning of the observed period.

In equation (4) the parameters of most interest are the deposition velocity a and the resuspension rate r which can be determined by experiments.

Experiments

As above mentioned, a wind tunnel was designed for the dust load investigation. Unlike in a full-scale room, the environmental conditions close to the test surface are well defined in the tunnel. The inlet of the wind tunnel can hold screens to produce different turbulence levels in the working section. The wind tunnel itself is placed in a closed room where the airborne dust concentration is controlled to stable levels.

The deposited dust is measured by vacuum cleaning the working surfaces in the wind tunnel with a special sampling head after running the experiment for a certain time. The dust is collected on a filter which is hold by the sampling head. In order to determine the amount of sampled dust the filter is weighed before and after sampling. Thereby it has to be assumed that the dust load is evenly distributed on the working surfaces and consequently the deposition and resuspension are constant over the corresponding surface of a certain orientation. A more detailed description of the experimental set-up, of the measuring equipment and results of a first series of dust load measurements can be found in [2]. For all the presented experiments talcum powder is used as artificial dust which has a mean diameter of 10 μm. The smallest particles are 0.1 μm and the largest 30 μm.

With the presented measuring method only the dust load Φ can be measured but not the deposition velocity a and the resuspension rate r individually. Due to equation (4), Φ is defined by the three unknown parameters Φ_0, a and r. Hence, to determine a and r with the presented experimental set-up, Φ has to be measured at three different points of time, namely at t_0, t_1 and t_2:

$$\Phi_0 = 0 \tag{6}$$

$$\Phi_1 = \left(\Phi_0 - \frac{aC}{r}\right) e^{-rt_1} + \frac{aC}{r} \tag{7}$$

$$\Phi_2 = \left(\Phi_1 - \frac{aC}{r}\right) e^{-r(t_2-t_1)} + \frac{aC}{r} \tag{8}$$

where $C = \overline{c_e(x, y, z)}$ is the space-mean particle concentration in the wind tunnel.

By measuring the dust load on three different surface orientations, namely upward-facing surfaces, vertical surfaces and downward-facing surfaces, deposition velocity and resuspension rates can be determined for floor, walls and ceiling.

Deposition

The experimentally investigated results can be compared with the theory mentioned in literature, e.g. [3, 4, 5]. The deposition velocity is determined by gravitational settling, molecular diffusion (Brownian motion), eddy turbulent diffusion, electrostatic forces and thermopheresis.

A model is introduced by [5] where particle transport through the boundary layer occurs by sedimentation, Brownian motion and eddy turbulent diffusion. The deposition velocity for the three surface orientations upward-facing, vertical and downward-facing is thus described as

$$a_F = \frac{a_g}{1 - exp\left(-\frac{\pi}{2}\frac{a_g}{\sqrt{DK_e}}\right)} \tag{9}$$

$$a_W = \frac{2}{\pi}\sqrt{DK_e} \tag{10}$$

$$a_C = \frac{a_g}{exp\left(\frac{\pi}{2}\frac{a_g}{\sqrt{DK_e}}\right) - 1} \tag{11}$$

where a_g is the gravitational settling velocity, D is the diffusion coefficient and K_e is the turbulent intensity parameter.

D increases as particle diameter becomes smaller, resulting in an increase in deposition coefficient. Thus in equations (9), (10) and (11), small particles $\sqrt{DK_e}$ dominates the deposition velocity. For large particles the effect of sedimentation may overwhelm the effect of diffusion and turbulence. Hence, for surfaces facing upwards $a_F \to a_g$ when the particles are large enough and for the ceiling $a_C \to 0$.

By not including thermopheresis in this model, it is assumed that the surfaces have the same temperature as the air. For indoor environments the effect of thermopheresis cannot be neglected since mostly temperature differences of some degrees between surfaces and air are observed. However, in the wind tunnel experiments presented in this paper, isothermal environmental conditions can be assumed. According to [6] electrostatic charge of surfaces and particles have a large influence on deposition and adhesion forces. Nevertheless, in a first step it is not considered in these experiments since an accurate method to measure the charge was not available.

Resuspension

Particle resuspension from a surface involves a complex interaction of different forces including adhesion of particles to the surface as well as fluid drag and lift forces. While rather good models describing the deposition can be found, only basic approaches exist to model resuspension. Two different models to describe resuspension are often used. The first is based on the assumption that the balance between adhesion and lift forces of a particle determines whether it resuspends or not. It assumes that when the lift force due to fluid dynamic forces is larger than the adhesion forces, the particle will be removed from the surface. Because resuspension occurs in spite of the fact that the surface forces are very strong, the second model, introduced by [7], considers that particle resuspension is not instantaneous but takes place over a period of time. It supposes that a particle can be resuspended from a surface when it accumulates enough energy to detach from the adhesive potential.

However, there is an agreement between the different models that all forces are proportional to $(particle\, diameter)^n$, where for the adhesion forces $n = 1$ and for the the removal forces $n \geq 2$. Hence, the adhesive force for particles less than $10\,\mu$m is much greater than the other forces to which the particles are exposed. While individual particles less than $10\,\mu$m are not likely to be removed from the surface, they can easily resuspend when they adhere to one another and build a larger agglomerate.

RESULTS

In Figures 1 and 2 the deposition velocity a and the resuspension rate r are shown as functions of the turbulent kinetic energy of the air. This energy is described as

$$k_0 = 1.5\,(tu\,u)^2 \qquad (12)$$

where tu is the turbulence level and u is the air velocity in the tunnel.

Corresponding to the equations (9) to (11) the deposition velocity on the floor is much higher than on surfaces with other orientations. According to the theory, the increase of a due to increased turbulence intensity should be the smallest for the floor and the highest on the ceiling. Actually, it is higher for the floor. This phenomenon could be caused by particles resuspended in the wind tunnel section upstream of the working section and deposited again in the working section.

The deposition velocity on walls and ceiling seems to be very small compared with the floor. But considering the total surface area which is covered by all the walls and the ceiling of a room, the total mass of dust deposited on these surfaces is not negligible

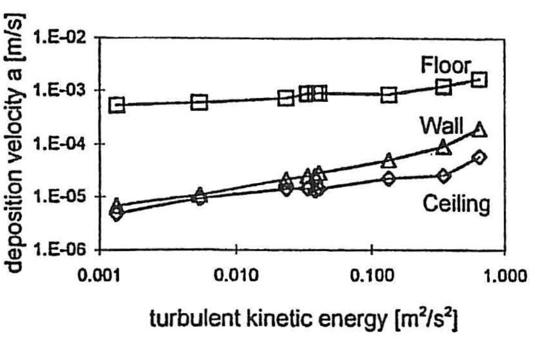


Figure 1: Deposition velocity a

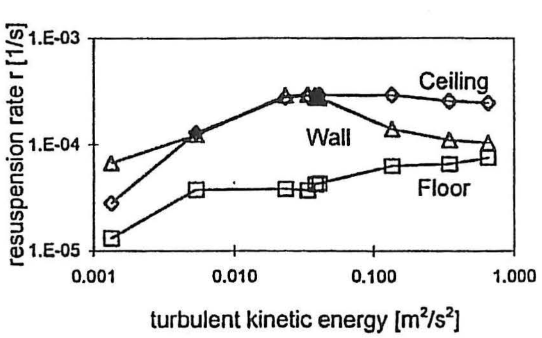


Figure 2: Resuspension rate r

at all. It can become more than 20 % of the amount deposited on the floor. Besides, the deposition velocity of small particles is, as above mentioned, dominated by the diffusion and the turbulence and therefore independent on surface orientation. Considering that just these small particles affect the health of people mostly since large particles are not respirable, it is obvious that the deposition and removal processes on walls and ceilings are rather important.

Figure 2 shows that the resuspension rate is the lowest for the floor and the highest for the ceiling. This result can be explained with the influence of the gravity force. However, some unexpected results can be observed. The resuspension rates on wall and ceiling reach a maximum at a certain turbulence intensity level and decrease again with increased turbulence. A complicated interaction between different forces might be the reason, e.g. more electrostatic force is induced at increased air velocity which leads to increased adhesion force [8].

Figure 3 represents simulated developments of the dust deposited on all surfaces of a room with the geometry $5 \times 4 \times 3$ m. The average air velocity is 0.1 m/s and the turbulence level 60 %. These are typical conditions in living rooms. The mean particle concentration in the room is $7e^{-4}$ kg/m^3.

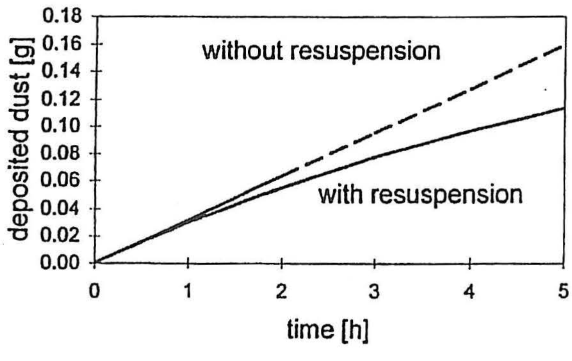


Figure 3: Deposited dust on all surfaces, simulated example

The amount of deposited dust is considerable higher in the case of no resuspension, namely about 40 % more than in the case with resuspension after a period of 5 h. These results show clearly that resuspension of particles from surfaces cannot be neglected when investigating the health risk of a room.

DISCUSSION

The presented functions to model the measured deposition and resuspension rate of particles correspond well with the reported literature. The model is kept as simple as possible in order to make it easy to implement in an existing CFD code. However, to translate these functions obtained in the wind tunnel to full-scale rooms, more investigations have to be done. Thermopheresis and electrostatic charge have to be considered to be able to simulate a real room, and deposition velocity and resuspension rate have to be determined for different particle sizes. In a further step the influence of different kinds of surfaces, of the relative humidity in the air and of different kinds of dust on these processes have to be estimated.

ACKNOWLEDGEMENTS

This research was supported financially by the Danish Technical Research Council (STVF) as a part of the research programme "Healthy Buildings" 1993 - 1997 and the Swiss National Science Foundation (SNF), research number NF 21-45778.95.

References

[1] A.J.H Goddard, M. Byrne, C. Lange, and J. Roed. Aerosols indoors: Deposition on indoor surfaces. *Air Infiltration Review*, 16(2):1–4, March 1996.

[2] P. Lengweiler, P.V. Nielsen, A. Moser, P. Heiselberg, and H. Takai. Experimental method for measuring dust load on surfaces in rooms. In D.J. Moschandreas, editor, *Design, construction and operation of healthy buildings*, chapter Building Investigation, pages 105–109. ASHRAE, 1998.

[3] W.W. Nazaroff and G.R. Cass. Mass-transport aspects of pollutant removal at indoor surfaces. *Environment International*, 15:567–584, 1989.

[4] J.G. Crump and J.H. Seinfield. Turbulent deposition and gravitational sedimentation of an aerosol in a vessel of arbitary shape. *J. Aerosol Science*, 12(5):405–415, 1981.

[5] J. Corner and E.D. Pendlebury. The coagulation and deposition of a stirred aerosol. *Proc. Phys. Soc.*, B64:645–654, 1951.

[6] P.H. McMurry and D.J. Rader. Aerosol wall losses in electrically charged chambers. *Aerosol Science and Technology*, 4:249–268, 1985.

[7] M.W. Reeks, J. Reed, and D. Hall. On the resuspension of small particles by a turbulent flow. *J. appl. Phys.*, 21:574–589, 1988.

[8] B.W. Shaw. *Use of a convective emission chamber to study particle resuspension.* PhD thesis, University of Illinois at Urbana-Champaign, 1994.

KEYWORDS

Aerosol, CFD, Deposition, Modelling, Particles

RECENT PAPERS ON INDOOR ENVIRONMENTAL ENGINEERING

PAPER NO. 84: P.V. Nielsen: *Airflow in a World Exposition Pavilion Studied by Scale-Model Experiments and Computational Fluid Dynamics.* ISSN 1395-7953 R9825.

PAPER NO. 85: P.V. Nielsen: *Stratified Flow in a Room with Displacement Ventilation and Wall-Mounted Air Terminal Devices.* ISSN 1395-7953 R9826.

PAPER NO. 86: P.V. Nielsen: *The Selection of Turbulence Models for Prediction of Room Airflow.* ISSN 1395-7953 R9828.

PAPER NO. 87: K. Svidt, G. Zhang, B. Bjerg: *CFD Simulation of Air Velocity Distribution in Occupied Livestock Buildings.* ISSN 1395-7953 R9831.

PAPER NO. 88: P. V. Nielsen, T. Tryggvason: *Computational Fluid Dynamics and Building Energy Performance Simulation.* ISSN 1395-7953 R9832.

PAPER NO. 89: K. Svidt, B. Bjerg, S. Morsing, G. Zhang: *Modelling of Air Flow through a Slatted Floor by CFD.* ISSN 1395-7953 R9833.

PAPER NO. 90: J.R. Nielsen, P.V. Nielsen, K. Svidt: *The Influence of Furniture on Air Velocity in a Room - An Isothermal Case.* ISSN 1395-7953 R9843.

PAPER NO. 91: P. Lengweiler, J.S. Strøm, H. Takai, P. Ravn, P.V. Nielsen, A. Moser: *Dust Load on Surfaces in Animal Buildings: An Experimental Measuring Method.* ISSN 1395-7953 R9844.

PAPER NO. 92: P. Lengweiler, P.V. Nielsen, A. Moser, P. Heiselberg, H. Takai: *Deposition and Resuspension of Particles: Which Parameters are Important?* ISSN 1395-7953 R9845.

PAPER NO. 93: C. Topp, P.V. Nielsen, P. Heiselberg, L.E. Sparks, E.M. Howard, M. Mason: *Experiments on Evaporative Emissions in Ventilated Rooms.* ISSN 1395-7953 R9835.

PAPER NO. 94: L. Davidson, P.V. Nielsen: *A Study of Low-Reynolds Number Effects in Backward-Facing Step Flow using Large Eddy Simulations.* ISSN 1395-7953 R9834.

PAPER NO. 95: A. Nielsen: *VRML Programs for Room Ventilation Applications.* ISSN 1395-7953 R9846.

PAPER NO. 96: E. Bjørn, P.V. Nielsen: *CFD Simulations of Contaminant Transport between Two Breathing Persons.* ISSN 1395-7953 R9809.

PAPER NO. 97: C. Topp, P.V. Nielsen, P. Heiselberg: *Modelling Emission from Building Materials with Computational Fluid Dynamics.*. ISSN 1395-7953 R9915.

PAPER NO. 98: H. Brohus: *Influence of a Cooled Ceiling on Indoor Air Quality in a Displacement Ventilated Room Examined by Means of Computational Fluid Dynamics.* ISSN 1395-7953 R9920.

PAPER NO. 99: P. Lengweiler, A. Moser, P.V. Nielsen: *New Functions to Model Measured Deposition and Resuspension Rates of Particles.* ISSN 1395-7953 R9924.

Complete list of papers: http://iee.civil.auc.dk/i6/publ/iee.html

ISSN 1395-7953 R9924

Dept. of Building Technology and Structural Engineering
Aalborg University, October 1999
Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark
Phone: +45 9635 8080 Fax: +45 9814 8243
http://iee.civil.auc.dk